HADRONIC JOURNAL 47, 183 - 206 (2024)
DOI 10.29083/HJ.47.02.2024/SC183

GENERALIZED UNCERTAINTY RELATIONS, GENERALIZED COMPTON WAVELENGTH AND PARTICLES IN A QUANTUM FOAM DESCRIBED BY A VARIABLE ENERGY DENSITY

David Fiscaletti
SpaceLife Institute – Via Roncaglia 35
S. Lorenzo in Campo (PU), Italy
spacelife.institute@gmail.com

Received February 9, 2024

Abstract

A model of a dynamic three-dimensional quantum vacuum based on energy fluctuations of a granular space is considered as the keystone for the beyond Standard Model physics. By starting from a generalized version of uncertainty relations, a generalized Compton wavelength is defined which provides a unifying re-reading of elementary particles and black holes and an emergent interpretation of the Standard Model particles. Perspectives of this model as regards the treatment of Higgs boson and some relevant issues of the Standard Model are explored.
Key words: three-dimensional dynamic quantum vacuum, variable quantum vacuum energy density, generalized uncertainty relations, generalized Compton wavelength, beyond Standard Model physics.

1. Introduction

20^{th} century theoretical physics introduced the concept of a unified quantum vacuum, which is not simply a purely geometrical container but is something endowed of an intrinsic energy density subtending the observable forms of matter, energy and space-time and ruling the processes on all space-time scales. However, despite the vacuum energy density appears in the cosmological constant as well as in quantum physics as zero-point energy, the physics of the previous century meets problems in order to provide a satisfactory interpretation of the so-called "empty space", intended as a phenomenon which is associated with the non-existence in a region of fields, elementary particles and massive objects. In the Standard Model of particle physics it looks as if the quantum features of the vacuum, associated with its energy density and the difference between real and virtual particles, do not receive adequate attention.

The Standard Model – despite its extraordinary predictive power in the description of the elementary particles of matter and their interactions up to at least a few TeV and the recent discovery of the Higgs boson – is affected by several flaws that suggest the necessity to provide an extension of this theory, namely to develop what can be called a "beyond Standard Model physics" [1-4]. In this regard, in particular, one must face the problem to explain the smallness of the electroweak scale, the origin of tiny neutrino masses, the matter–antimatter asymmetry in the universe and, above all, the fact that the Standard Model can actually explain only the 5% of the things existing in the universe. In fact, in order to explain, on one hand, the accelerated expansion of the universe and, on the other hand, the existence of large scale dynamical phenomena, i.e. the formation of structures in the universe and their persistence today, the dynamics of galaxies and galaxy clusters, a mysterious form of diffuse dark energy probably pervading all corners of the universe and an elusive electrically neutral "dark matter" that is only subjected to gravitational interaction, are respectively invoked. Despite some different proposals of extensions of the Standard Model exist in the literature (and, in particular, the different perspectives of treatment of dark energy and dark matter [5-13]), all these fundamental topics require an adequate explanation yet.

In order to provide new perspectives of explanation, inside an unifying and emergent picture, of the existence of an intrinsic energy density describing an "empty space" intended as a primary physical reality as well as to develop a beyond Standard Model physics, I have recently developed a model of a three-dimensional (3D) dynamic quantum vacuum (DQV) which has the merit to build a bridge between quantum mechanics and general relativity [14-24]. In this model, the notion of a fundamental non-local quantum geometry and the notion of a space-time emerging from the deepest processes situated at the level of quantum gravity can be embedded and unified inside the same scheme. In the picture of a Planckian metric, this approach shows how and in what sense the fundamental background space of physical processes is a 3D DQV where each particle is determined by elementary

reduction-state (RS) processes of creation/annihilation of virtual particles-antiparticles pairs corresponding to opportune changes of an elementary energy density of space.

The fundamental insight of the 3D DQV model is that dark energy and dark matter do not exist as primary physical realities but constitute only manifestations of an underlying fundamental variable quantum vacuum energy density, which is the origin of the curvature of space-time too [14-24]. In other words, in this model, ordinary matter, dark matter and dark energy can be seen as emergent structures, forms of collective organizations, which come into existence as the upper manifestations of specific excited states of the DQV, which correspond to specific fluctuations of the quantum vacuum energy density.

On the basis of the model of the 3D DQV developed by the author of this paper, the absence of material objects in the outer intergalactic space, corresponds to the Planck energy density:

$$\rho_{PE} = \frac{m_p \cdot c^2}{l_p^3} \quad (1)$$

where m_p is Planck's mass, c is the light speed and l_p is Planck's length. The Planck energy density (1), which is the maximum value of the energy density of space and physically corresponds to the total average volumetric energy density, owed to all the frequency modes possible within the visible size of the universe, represents the origin of "empty" universal space in which there are no material objects and can be interpreted as a sort of "ground state" of the 3D quantum vacuum.

The appearance of ordinary matter can be associated to a specific diminishing of the quantum vacuum energy density corresponding to elementary reduction-state (RS) processes of creation/annihilation of virtual particle/antiparticle pairs. In other words, matter has origin from excited states of the 3D DQV characterized by a less energy density than the ground state. The excited state of the 3D DQV corresponding to the appearance of a material particle is defined (in the centre of that particle) by the energy density

$$\rho_{qvE} = \rho_{pE} - \frac{mc^2}{V} \quad (2)$$

and therefore by the change of the energy density

$$\Delta\rho_{qvE} \equiv \rho_{pE} - \rho_{qvE} = \frac{mc^2}{V} \quad (3),$$

with respect to the ground state, depending on the amount of mass m and the volume V of the particle.

Dark energy manifests itself as a collective emerging phenomenon of specific quantum vacuum energy density fluctuations on the basis of relation

$$\rho_{DE} \cong \frac{35Gc^2}{2\pi\hbar^4 V}\left(\frac{V}{c^2}\Delta\rho_{qvE}^{DE}\right)^6 \quad (4)$$

where $\hbar$ is Planck's reduced constant, G is Newton's gravitational constant, V is the volume of the region under consideration, $\Delta\rho_{qvE}^{DE}$ are the specific fluctuations of the quantum vacuum energy density generating the action of the dark energy density. Finally, the action of dark matter, which is invoked to explain the rotation curves of galaxies, is associated with a more fundamental notion of polarization of the vacuum characterized by a fluctuating viscosity $\mu(t)$, which is generated by a "perturbative" fluctuation of the quantum vacuum energy density given by relation

$$\Delta\rho_{perturbative} = \frac{\mu\hbar c^2}{nVl_p^2\Delta\rho_{qvE_0}} \quad (5)$$

(where n is the number of the virtual particles in the volume into consideration and $\Delta\rho_{qvE_0}$ is the change of the quantum vacuum energy generating the appearance of matter at a rest mass). In this picture, the stabilized behaviour of the speed of the arms of spiral galaxies, with increasing distance from the core of the galaxy, as predicted by observations [17, 21, 24], is explained in terms of an exchange of the energy of the rotating galactic matter with the quantum vacuum fluctuations, which is determined by the perturbative fluctuation of the quantum vacuum energy density (5).

In this paper, our purpose is to explore the unifying scenarios which are introduced by the view of a variable energy density of a 3D DQV intended as a primary physical reality, towards a beyond Standard Model physics: we want to show how the ordinary Standard Model particles can be seen as the result of processes of collective organization regarding the activity of quantum vacuum energy density fluctuations at an ultimate scale, ultimately linked with the Planck scale, where particles and black holes are unified. The structure of the paper is the following. In section 2 we analyse the geometrodynamic properties of the microscopic structure of the 3D DQV by considering a modification of the Heisenberg uncertainty relations expressed by opportune generalized uncertainty relations and we explore how the current theoretical frameworks as well as experimental observations provide physical constraints on the size of the modifications of the geometry of space-time associated with this approach. In section 3 we will show in what sense the 3D DQV model leads to suggestive unifying perspectives of the microscopic regime of elementary particles and the macroscopic domain of black holes and we will analyse how, at a unifying scale of elementary particles and black holes – defined by an opportune generalized Compton wavelength – the action of the quantum vacuum energy density fluctuations leads to an emergent interpretation of Standard Model particles. In section 4, we introduce some new insights and keys of reading as regards the interpretation of Higgs boson as well as other important issues of the Standard Model. Finally, in section 5, we summarize the main results of the paper.

2. The generalized uncertainty relations in the three-dimensional dynamic quantum vacuum and its physical constraints

One of the main challenges in current theoretical physics lies in finding a satisfactory synthesis of quantum theory and general relativity into a unified structure. If various approaches have been developed towards such a theory in order to face quantum gravity, a major difficulty is represented by the lack of experimental evidence of quantum gravitational effects. On the other hand, the quantization of space-time itself can determine experimental effects, in the sense that the existence of a minimal measurable length physically leads to a modification of the Heisenberg uncertainty relation at an opportune scale near the Planck scale, which depends of a deformation parameter.

In the model of 3D DQV considered in this paper, the microscopic structure of the underlying background of processes is characterized by a deformation of the geometry expressed by the following generalized uncertainty relations, which are valid at the Planck scale:

$$\Delta x \Delta p \geq \frac{\hbar}{2}\left(1 + \beta l_p^2 \frac{\Delta\rho_{qvE}^2 V^2}{\hbar^2 c^2}\right) \quad (6) \quad [25].$$

In equation (6) β is a fluctuating parameter which expresses the fact that here space-time fluctuations fix the minimal length scale only on average, in analogy with what happens in quantum foam scenarios such as loop quantum gravity as well as cellular automaton interpretation of quantum mechanics [26-33]. The second term, $\frac{\hbar}{2}\beta l_p^2 \frac{\Delta\rho_{qvE}^2 V^2}{\hbar^2 c^2}$ appearing in relation (6) measures the degree of violations of the Heisenberg uncertainty relations at scales that approach the Planck scale.

The modifications of the Heisenberg uncertainty relations represented by equation (6) can be associated to the consideration of a quantization of space-time and thus to the existence of a minimum measurable length scale of the form

$$\Delta x_{min} = l_p\sqrt{\beta} \quad (7).$$

The relation between the existence of a minimal length and a modification of the Heisenberg position-momentum uncertainty principle at the Planck scale has been recently considered by several authors in many approaches to quantum gravity, such as string theory, doubly special relativity and in explorations of the properties of black holes [34-36].

As regards the different formulations of the generalized/modified uncertainty relations, in the previous decade an intense debate focused on the experimental predictions about the size of these modifications, namely about the bounds of the dimensionless parameter measuring the deviations from the standard Heisenberg relations. As a consequence of these results, the following scenario emerges as regards the constraints on the parameter β appearing in equation (6).

On one hand, a first estimate of constraints on the value of the parameter β comes by taking into account the absence of deviations from the standard Heisenberg principle at the electroweak scale, which leads to express the second term of right side of equation (7) as

$$\beta l_p^2 \frac{\Delta\rho_{qvE}^2 V^2}{\hbar^2 c^2} = \beta \frac{\rho_{qvE}^{EW}}{\rho_p} \ll 1 \quad (8)$$

thus implying $\beta \ll 10^{34}$. On the other hand, the study of Bushev et al. [37] provided an estimate of the upper bound of the parameter β of $\beta < 4 \cdot 10^4$ by considering the dynamical implications of the contorted commutator on the oscillations of a high-Q mechanical resonator with a sub-kilogram mass m of the resonating mode, thus probing deformed commutators with macroscopic harmonic oscillators. In Bushev's approach, one can consider a deformation in $\beta\hat{p}^4$ of the usual harmonic oscillator Hamiltonian and thus an Hamiltonian of the form:

$$H = \frac{\hat{p}^2}{2m} + \frac{1}{2}m\Omega_0^2\hat{x}^2 + \frac{\beta\hat{p}^4}{3m(M_{pl}c)^2} \quad (9)$$

where Ω_0 is the unperturbed value of the resonance frequency. The Hamiltonian (9) determines a amplitude dependence of the resonance frequency whose resolution is expressed by relation

$$\frac{\delta\Omega(A)}{\Omega_0} = (m_{eff}\Omega_0 A/M_{pl}c)\beta \quad (10)$$

where $\delta\Omega$ is the deviation of the amplitude-dependent resonance frequency $\Omega(A)$ from the unperturbed value Ω_0, m_{eff} is the effective mass of the mode and A is the oscillation frequency. On the basis of equation (10), it is possible to set an upper limit for the model parameter β and, in this regard, in particular, Bushev's group performed an experiment with a quartz BAW resonator, estimating a limit of $\beta < 4 \cdot 10^4$. Moreover, in [38] an evaluation of the upper bound of $\beta < 10^{12}$ was found by measuring the timescale in which large molecular wave packets double its initial width.

A crucial topic connected to the modification of the Heisenberg uncertainty relations given by equation (6) lies in the fact that it corresponds to a deformation of the underlying canonical commutator, in the sense that these generalized uncertainty relations lead to the following modified commutator:

$$[x, p]_\beta = i\hbar\left(1 + \beta l_p^2 \frac{\Delta\rho_{qvE}^2 V^2}{\hbar^2 c^2}\right) \quad (11).$$

Up to date, no effect of a modified canonical commutator of the kind (11) has been observed in experiments. As regards the modified commutator (11) of the 3D DQV model, it must be emphasized that the Planck scale modifications correspond to $\beta \approx 1$ and are therefore untested. On the other hand, it must be emphasized that the modification of the commutator at quantum gravity regime is not unique in the sense that can also be expressed in other versions and experiments that can, in principle, discriminate between the various approaches [39].

Different theoretical frameworks provide bounds on β of gravitational origin, by considering a deformation of the Hawking temperature of a Schwarzschild black hole when computed through generalized uncertainty relations, thus yielding to the following result

$$\beta = -\frac{\pi^2 M^2}{4M_p^2}\varepsilon^2 \quad (12)$$

where ε is the deformation parameter associated with the horizon radius of the black hole of mass M. In this regard, if one invokes the measures of the precession of Mercury by considering the deformed metric

$$F(r) = 1 - \frac{2GM}{rc^2} + \varepsilon\frac{G^2M^2}{r^2c^4} \quad (13)$$

one obtains the following constrain on ε:

$$|\varepsilon| < 1{,}6 \cdot 10^{-4} \quad (14)$$

which implies the following bound on β:

$$|\beta| < 2 \cdot 10^{69} \quad (15)$$

Now, in the model of the 3D DQV explored in this paper, in affinity with the treatment of Scardigli et al. [40, 41], we want to show how one can obtain an exact value of the parameter β appearing in relation (6) by considering an opportune quantum deformation of a metric of the form (22) associated with the following Arnowitt-Deser-Misner mass

$$M_{ADM} = \frac{\Delta\rho_{qvE}V}{c^2}\left(1 + \frac{\hbar^2c^2}{\beta l_p^2\Delta\rho_{qvE}^2V^2}\right) \quad (16)$$

which derives from the generalized uncertainty relations (6) if the one considers the substitution

$$\Delta p \to \Delta p + \frac{\hbar^2c^2}{l_p^2\Delta p} \quad (17).$$

The Arnowitt-Deser-Misner mass (16) leads to define a quantum-modified Schwarzschild metric of the form

$$ds^2 = F(r)c^2dt^2 - F(r)^{-1}dr^2 - r^2d\Omega^2 \quad (18)$$

where

$$F(r) = 1 - \frac{2G\Delta\rho_{qvE}{}^3V^3}{M_{Pl}{}^2c^8r} + \varepsilon\frac{\hbar^2\Delta\rho_{qvE}\ V}{l_p^2M_{Pl}{}^2c^6r} \quad (19)$$

and $d\Omega^2 = d\theta^2 + sin^2\theta d\phi^2$ is the metric on the 3-sphere. The physical meaning of the metric (18) – equipped with equation (19) – lies in the fact that it determines the following expression for the horizon size

$$r_H = R_S' = \frac{2G\Delta\rho_{qvE}{}^3V^3}{M_{Pl}{}^2c^8}\left(1 + \varepsilon\frac{\hbar^2c^2}{l_p^2\Delta\rho_{qvE}^2V^2}\right) \quad (20)$$

which, in the different regimes of the quantum vacuum energy density, becomes

$$r_H \approx \begin{cases} \frac{2G\Delta\rho_{qvE}{}^3V^3}{M_{Pl}{}^2c^8} & if\ \Delta\rho_{qvE}V \gg M_{Pl}c^2 \\ \frac{2GM_{Pl}}{c^2}\left(1 + \frac{\hbar^2c^2}{\varepsilon l_p^2M_{Pl}^2c^2}\right) & if\ \Delta\rho_{qvE}V \approx M_{Pl}c^2 \\ \frac{2G\hbar^2}{\varepsilon l_p^2c^6} & if\ \Delta\rho_{qvE}V \ll M_{Pl}c^2 \end{cases} \quad (21).$$

In the regime where the first expression of (21) holds, which coincides with the standard Schwarzschild radius, one finds the following expression for the deformed standard Hawking temperature:

$$T = \frac{\hbar c^5}{8\pi k_BG\Delta\rho_{qvE}V}\left\{1 + \varepsilon\left[\frac{\hbar^2c^2}{l_p^2G\Delta\rho_{qvE}{}^2V^2} - \frac{M_{Pl}{}^4c^{16}}{2G^3\Delta\rho_{qvE}{}^6V^6}\right] + \cdots\right\} \quad (22).$$

On the other hand, by starting from the quantum-modified Schwarzschild metric (18) and by assuming the thermal character of the correction induced by the generalized uncertainty relations (6), one finds the following deformed Hawking temperature of a Schwarzschild black hole:

$$T = \frac{\hbar c^5}{8\pi k_B G \Delta\rho_{qvE} V}\left\{1 + \beta \frac{M_{Pl}{}^2 c^4}{4\pi^2 \Delta\rho_{qvE}{}^2 V^2} + \cdots\right\} \quad (23)\ [41].$$

Comparison between expressions (22) and (23) leads to relation

$$\beta \frac{M_{Pl}{}^2 c^4}{4\pi^2 \Delta\rho_{qvE}{}^2 V^2} = \varepsilon\left[\frac{\hbar^2 c^2}{l_P^2 G \Delta\rho_{qvE}{}^2 V^2} - \frac{M_{Pl}{}^4 c^{16}}{2G^3 \Delta\rho_{qvE}{}^6 V^6}\right] \quad (24).$$

Now, by taking into account that for any metric of the form (18) an effective Newtonian potential can be defined as

$$V(r) \cong \frac{c^2}{2}(F(r) - 1) \quad (25)$$

one obtains

$$F(r) = 1 + 2\frac{V(r)}{c^2} = 1 - \frac{2G\Delta\rho_{qvE}{}^3 V^3}{M_{Pl}{}^2 c^8 r} - \frac{6G^2 \Delta\rho_{qvE}{}^6 V^6}{M_{Pl}{}^4 c^{16} r^2}\left(1 + \frac{mc^2}{\Delta\rho_{qvE} V}\right) - \frac{41}{5\pi}\frac{G^3 \Delta\rho_{qvE}{}^9 V^9}{M_{Pl}{}^6 c^{24} r^3}\left(\frac{l_P c^4}{G\Delta\rho_{qvE} V}\right)^2 \quad (26).$$

Finally, if one makes the identification

$$\varepsilon\left[\frac{\hbar^2 c^2}{l_P^2 G \Delta\rho_{qvE}{}^2 V^2} - \frac{M_{Pl}{}^4 c^{16}}{2G^3 \Delta\rho_{qvE}{}^6 V^6}\right] = -\frac{6G^2 \Delta\rho_{qvE}{}^6 V^6}{M_{Pl}{}^4 c^{16} r^2}\left(1 + \frac{mc^2}{\Delta\rho_{qvE} V}\right) - \frac{41}{5\pi}\frac{G^3 \Delta\rho_{qvE}{}^9 V^9}{M_{Pl}{}^6 c^{24} r^3}\left(\frac{l_P c^4}{G\Delta\rho_{qvE} V}\right)^2 \quad (27)$$

equation (23) yields the following result for the parameter β:

$$\beta \frac{M_{Pl}{}^2 c^4}{4\pi^2 \Delta\rho_{qvE}{}^2 V^2} = \frac{41}{40\pi}\left(\frac{l_P c^4}{G\Delta\rho_{qvE} V}\right)^2 \quad (28)$$

namely

$$\beta = \frac{82\pi}{5} \quad (29)$$

compatibly with the result obtained in [41].

An important consequence of the generalized uncertainty relation (6) lies in its influence on low energy experiments such as the Lamb shift and the Landau levels by virtue of the fact that any system with a well-defined quantum (or classical) Hamiltonian is perturbed near the Planck scale by a correction term of the form

$$H_1 = \frac{\beta\hbar^4 c^2}{\Delta\rho_{qvE} V} \quad (30).$$

Thus, in the case of a Hydrogen atom the effect of the generalized uncertainty relation (6) for the Lamb shift of the ground state is the following:

$$\frac{\Delta E_{0(Generalized\ uncertainty\ relations)}}{\Delta E_0} \approx 10\beta \frac{\Delta\rho_{qvE} V E_0}{M_{Pl}^2 c^4} \approx 0{,}47 \cdot 10^{-48}\beta \quad (31)$$

where E_0 is the energy of the ground state. The result (31) implies that, if one assumes $\beta \approx 1$, then a non-zero, but virtually un-measurable effect of the generalized uncertainty relations (6) on quantum gravity, is predicted; instead, if this assumption

is not considered, the current accuracy of precision measurement of Lamb shift of about 1 part in 10^{12} sets the following upper bound

$\beta < 10^{36}$ (32).

Since the bound (32) is weaker than the one associated with the electroweak scale, the result (32) seems to indicate the existence of a new and intermediate scale between the electroweak and Planck scale [42].

In analogous way, one can show that the generalized uncertainty relation (6) modifies the Landau levels of a system in a constant magnetic field with a cyclotron frequency $\omega_c = \frac{eBc^2}{\Delta\rho_{qvE}V}$, on the basis of relation:

$$\frac{\Delta E_{0(Generalized\ uncertainty\ relations)}}{\Delta E_0} \approx \beta \frac{\Delta\rho_{qvE}V\hbar\omega_c}{M_{Pl}^2 c^4} \quad (33).$$

This means that, in the case of an electron in a magnetic field of 10 T, $\omega_c = 10^3 GHz$, one obtains:

$$\frac{\Delta E_{0(Generalized\ uncertainty\ relations)}}{\Delta E_0} \approx 2{,}30 \cdot 10^{-54}\beta \quad (34).$$

The result (34) implies therefore that, if β is assumed of the order of 1, again the correction to the Landau levels is too small to be measured; instead, on the basis of the current measurement of accuracy of 1 part in 10^3 leads to the following constraint

$\beta < 10^{50}$ (35)

which itself implies the existence of an intermediate scale between electroweak and Planck scale [42].

3. From the generalized Compton wavelength to an emergent interpretation of the Standard Model particles

The variable energy density of the 3D DQV can be associated to a deformation of the geometry of the background which has the fundamental property of leading to a suggestive unification of the microscopic regime of elementary particles and the macroscopic domain of black holes, in other words to the existence of a fundamental scale where Compton wavelength and Schwarzschild radius are unified.

The possibility that, at around the Planck scale, elementary particles and black holes receive a unifying description, has been recently explored by various authors [43-50]. In the theory developed by the author of this paper, by following the mathematical treatment considered in [43, 45, 48, 50], the crucial result lies in the fact that, by starting from the generalized uncertainty relations (6), one can define a generalized Compton wavelength in the linear regime, given by relation

$$R_C' = \frac{\hbar c}{\Delta\rho_{qvE}V} + \beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar\ c} \quad (36)$$

and, above all, a more general, unified expression for the generalized Compton wavelength and Schwarzschild radius, which is also valid in the quadratic regime, given by relation

$$R'_C = R'_S = \sqrt{\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2} \quad (37).$$

The physical meaning of equation (37) is that the fundamental quantum vacuum energy density fluctuations characterizing the underlying foam of virtual particles represented by the 3D DQV, imply the existence of a physical relation between the uncertainty principle on the scale of elementary particles and the regime of black holes in macrophysics. In other words, in the light of equation (37), one can say that the connecting loop between microphysics and macrophysics is represented by elementary objects of the Planck scale, namely sub-Planckian black holes with a size of order of their Compton wavelength, which are generated by the geometrodynamic properties of the variable quantum vacuum energy density ultimately associated to the foam of the virtual particles of the vacuum. The generalized Compton wavelength (37), which ultimately emerges from the generalized uncertainty relations (6), shows also that a unifying treatment of Casimir effect and cosmological wormholes is possible: the ultimate origin of the geometry of wormholes is represented by processes involving the 3D DQV and, here, the curvature and scale factor of the universe appear as upper manifestations of the elementary fluctuations of the quantum vacuum energy density as well as of the fluctuating parameter appearing in the generalized uncertainty relations [25].

Now, in this chapter, we want to show how the generalized Compton wavelength and Schwarzschild radius, given by equation (37), allows us to develop an interpretation of Standard Model particles as emerging events from the quantum vacuum energy density fluctuations, by following a process of collective organization. In this regard, by using the third quantization formalism developed in [51], in the geometry of the 3D DQV ruled by the generalized uncertainty relations (6), we suggest that the evolution of the wave function Ψ of each micro-universe (which is a function of the scale factor a of the universe and of the scalar fields φ associated with the quantum vacuum energy density fluctuations as well as the polarization of the vacuum) is ruled by a peculiar form of Wheeler-DeWitt (WDW) equation, intended as an equation of background, a real "equation of everything" where all the possibilities of the physical world are written in timeless form:

$$\ddot{\Psi} + \frac{k\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right)^{3/2} \Delta\rho_{qvE}}{ac^2\sqrt{\alpha}} \dot{\Psi} + \omega^2(a)\Psi = 0 \quad (38).$$

In equation (38) the following important quantities appear: $\dot{\Psi} = \frac{\partial\Psi}{\partial a}$, α is the fine-structure constant, ω is the mode frequency linked with the scale factor, $\Delta\rho_{qvE}$ are the quantum vacuum energy density fluctuations corresponding to elementary RS processes of creation/annihilation of virtual particle/antiparticle pairs and, finally, k is an adimensional parameter corresponding to the size of the condensate of virtual sub-particles of the 3D DQV, namely represents a sort of effective parameter of density of

the virtual particles of the medium. Equation (38) may be defined as the "generalized WDW equation in 3D DQV".

On the basis of equation (38), each micro-universe can be seen as a structure which derives from the activity of opportune quantum vacuum energy density fluctuations at the ultimate unifying scale represented by the generalized Compton wavelength and Schwarzschild radius (37). The wave function Ψ satisfying WDW equation (38) and therefore describing the behaviour of each micro-universe of the landscape of the 3D DQV, namely its corresponding particle, can be expressed as

$$\hat{\Psi} = \frac{k\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right)^{3/2}\Delta\rho_{qvE}}{\sqrt{2\pi}\hbar l_p{}^2}\int d\rho\left(e^{ik\frac{\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right)^{3/2}\Delta\rho_{qvE}}{\hbar l_p{}^2}\varphi}\Psi_{\Delta\rho_{qvE}}(a)\hat{b}_{\Delta\rho_{qvE}} + e^{-ik\frac{\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right)^{3/2}\Delta\rho_{qvE}}{\hbar l_p{}^2}\varphi}\Psi^*_{\Delta\rho_{qvE}}(a)\hat{b}^\dagger_{\Delta\rho_{qvE}}\right) \quad (39).$$

In equation (39), the operators $\hat{b}_{\Delta\rho_{qvE}}$ and $\hat{b}^\dagger_{\Delta\rho_{qvE}}$ are the annihilation and creation operators which annihilate and create respectively micro-universes, namely particles, associated with corresponding quantum vacuum energy density fluctuations, whose action occurs at the generalized Compton wavelength, and obey the so-called "quantum Boltzmann statistics", or "Infinite statistics", described by the following commutation relations between the oscillators

$\hat{b}_k\hat{b}_l^\dagger - q\hat{b}_l^\dagger\hat{b}_k = \delta_{kl}$ (40)

where q is a deformation parameter. In the light of equation (40), one obtains that the generation of bosons and fermions emerge in the peculiar cases $q = \pm 1$.

Moreover, here the production of a micro-universe (and thus the manifestation of a corresponding particle) corresponds to the generation of an information in a cell of the 3D DQV given by the following relation:

$I = \frac{A}{l_p{}^2}$ (41)

where

$A = k\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right]$ (42)

is the area of the cell, which depends of the size of the condensate of the virtual sub-particles of the background. According to the approach based on equations (38)-(42), the following relevant consequences can be therefore derived. On one hand, one has

an informational scenario at the Planck scale able to give origin to compelling perspectives of unification between elementary particle physics and cosmology. On the other hand, one can choose opportunely the parameter k defining the size of the condensate of the virtual sub-particles of the medium in order to obtain the appearance of the desired particle of the Standard Model with its usual properties. In this regard, by using a fruitful result of the transactional approach [52-54], one can consider the possibility that the regime of ordinary Standard Model particles emerges as a phenomenon associated with the chronon scale $\frac{A^3}{l_p^2} \approx 10^{-13}cm$. Equation (41) implies that the generic micro-universe leads to the appearance of ordinary Standard Model particles if the information created in a cell satisfies relation $I^3 l_p \approx 10^{-13}cm$, namely, taking account of equation (42),

$$\frac{k^3}{l_p^5}\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right]^3 \approx 10^{-13}cm \quad (43).$$

Equation (42) expresses in what sense the generalized Compton wavelength and the size of the condensate of the virtual sub-particles of the 3D DQV lead in a direct way to the minimum size of each spatial length characterizing the Planck lattice of the 3D DQV background, which gives rise to the appearance of the "bare" state of a particle, i.e. to the chronon scale. In other words, in the light of equation (43), the chronon scale of ordinary Standard Model particles can be interpreted as the emergence scale of processes of collective organization of opportune condensates of the virtual sub-particles of the 3D DQV which take place at the generalized Compton wavelength and are mathematically described by the wave function (39).

When the information associated with the fundamental cells of the multiverse satisfies relation $I^3 l_p \approx 10^{-13}cm$, namely equation (43), then the wave function of the micro-universe (39) undergoes a sort of quantum jump which leads to the appearance of the skeleton of a particle. The resulting event can be described through an internal wave function factor (inaccessible by direct observation) $\phi(\tau')$, null at the boundary and outside of the interval $\left[-\frac{I^3 l_p}{2c}, \frac{I^3 l_p}{2c}\right]$ where $I^3 l_p \approx 10^{-13}cm$, and whose evolution follows the law:

$$\begin{cases} -\hbar^2 \frac{\partial^2}{[\partial(2\pi\tau')]^2}\phi(\tau') = \left(\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right)^{3/2} \Delta\rho_{qvE}\right)^2 \phi(\tau')\ if\ \tau' \in \left[-\frac{I^3 l_p}{2c}, \frac{I^3 l_p}{2c}\right] \\ \phi(\tau') = 0 \qquad otherwise \end{cases}$$

(44).

On the basis of equation (44), it follows that the micro-universes described by the wave function (39) correspond to the usual real elementary particles when there is the following constraint regarding the quantum vacuum energy density fluctuations

$$\left(\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right)^{3/2}\Delta\rho_{qvE}\right)^2=n'\frac{\hbar c}{l^3 l_p}\quad(45)$$

where $n' = 0, ½, 1, 3/2, ...$ is an integer for odd solutions, a half-integer for even solutions. In correspondence, the micro-universes can be associated to the appearance of a boson or a fermion as a consequence of the specific value of the deformation parameter q. Hence, it follows that the "bare" mass of the ordinary material particles of the Standard Model can be seen as the result of opportune diminutions of the quantum vacuum energy density corresponding to opportune elementary RS processes of creation/annihilation of virtual particles on the basis of relation

$$mc^2=n'\frac{\hbar c}{l^3 l_p}\quad(46),$$

namely

$$mc^2=n'\frac{\hbar c}{\frac{k^3}{l_p^5}\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right]^3}\quad(47)$$

where

$$mc^2=\left(\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right)^{3/2}\Delta\rho_{qvE}\right)^2\quad(48)$$

namely it is the fluctuations of the quantum vacuum energy density acting at the generalized Compton wavelength that give origin to the appearance of the property of the mass of ordinary particles of the Standard Model. Equations (47) and (48) physically provide the constraint that establishes what is the relation between the geometry of the 3D quantum vacuum characterized by virtual particle/antiparticle pairs and the quantum jumps regarding elementary particles of the Standard Model described by the chronon scale and ruled by the ordinary quantum laws. The physical meaning of equations (47)-(48) is therefore the following: the quantum vacuum energy density fluctuations associated with the virtual sub-particles of the 3D DQV, which act at the generalized Compton wavelength and whose evolution, at the ultimate level, is ruled by the generalized WDW equation (38), can be considered as the ultimate elements which give rise to the appearance of particles of the Standard Model at the Planck scale and, conversely, can be considered as the Planck signature of Standard Model particles.

4. Interpretation of Higgs boson and perspectives as regards some issues of the Standard Model

Within the Standard Model, the masses of all kinds of fermions are provided by the Higgs mechanism, whose mathematical formalism is expressed in terms of two parameters, namely the quadratic mass term and the dimensionless quartic coupling, which turn out to be strictly associated with the Higgs vev and the Higgs mass, once

spontaneous symmetry breaking is applied. If in the Standard Model, over the years, the Higgs mass was studied in terms of a mixture of themes, such as unitarity, perturbativity (corresponding to the fact that the Higgs mass was to be expected to be of order of the electroweak scale), vacuum stability and radiative corrections, instead our model of 3D DQV, whose ultimate geometry is described by the generalized Compton wavelength (36), suggests the crucial perspective that the Higgs mass can be derived as an emergent fact from the fundamental properties of the vacuum too.

In our approach, the Higgs Lagrangian responsible of the generation of the mass terms for the W and Z bosons of weak generations can be expressed in the form

$$\mathcal{L}_H = \left|D_\mu \Psi\right|^2 - V(\Psi) \quad (49)$$

where Ψ is an opportune solution of the generalized WDW equation (38), namely has the form (39) in operator form, and the Higgs potential $V(\Psi)$ is

$$V(\Psi) = \mu^2 \Psi^+ \Psi + \lambda(\Psi^+ \Psi)^2 \quad (50)$$

where λ is a positive parameter. For $\mu^2 < 0$ the gauge symmetry $SU(2)_L \times U(1)_Y$ of electroweak interactions is broken to $U(1)_{em}$ and, in this process, the pseudo Goldstone bosons can be associated to the emergence of the massive W and Z bosons. In this context, we know that, in the Standard Model, the non-physical degrees of freedom determined by the Higgs doublet are removed in the Unitary gauge, where the Higgs doublet can be written as

$$\phi = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v+h \end{bmatrix} \quad (51)$$

where $v = \sqrt{\frac{-\mu^2}{\lambda}}$ and h is the excitation from the vev. As a consequence of (51), as is known, the Higgs potential of the Standard Model becomes

$$V(\psi) = \frac{1}{4}\lambda v^4 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 \quad (52)$$

which yields the following relation as regards the Higgs mass: $m_H^2 = 2v^2\lambda$.

Now, in our approach of the 3D DQV characterized by fundamental energy density fluctuations at the generalized Compton wavelength (37), in the Unitary gauge the Higgs doublet (51) becomes

$$\phi = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ \frac{1}{\left(k\left(\left(\frac{\beta \hbar c}{\Delta\rho_{qvE} V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE} V}{\hbar c}\right)^2\right)\right)^{3/2}} + h \end{bmatrix} \quad (53)$$

where h indicates the excitations of the 3D DQV from the vacuum expectation value ε which is related to the rest mass of the W boson as

$$\varepsilon = \frac{\sqrt{2}c^2}{g} M_W \quad (54)$$

where g represents the electroweak coupling constant. Then, taking account of the results obtained in [55], by applying the Unitary gauge constraint, in our model, the Mexican hat potential which corresponds to the action of the Higgs field may be expressed as

$$V(\psi)=\frac{1}{4}\lambda\frac{1}{\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right)^6}+\lambda\frac{1}{\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right)^3}h^2+$$

$$\lambda\frac{1}{\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right)^{3/2}}h^3+\frac{1}{4}\lambda h^4 \quad (55).$$

In other words, in our model, the parameter v invoked by the Standard Model is assimilated to the ultimate geometry associated with the generalized Compton wavelength. In equation (55) λ is a positive parameter which satisfies relation

$$\sqrt{\frac{\frac{\xi^2}{2\pi}k\omega m|\Psi|^2}{\lambda}}=\frac{1}{\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right)^{3/2}} \quad (56),$$

where ξ is the scattering length between the virtual sub-particles of the 3D DQV, and m is the mass of these virtual sub-particles. Equation (56) leads to the following result as regards the parameter λ:

$$\lambda=\left[\frac{\xi^2}{2\pi}k\omega m|\Psi|^2\right]^{1/2}\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right)^{3/2}, \quad (57).$$

Now, as regards the potential (55), it must be emphasized that the second term (that is quadratic in h) plays a crucial role, in the sense that it allows us to express the Higgs mass in terms of the properties of the 3D DQV at the generalized Compton wavelength as follows:

$$m_H^2=\frac{2\left[\frac{\xi^2}{2\pi}k\omega m|\Psi|^2\right]^{1/2}}{k^2\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar c}\right)^2\right)^{3/2}} \quad (58).$$

Equation (58) establishes the condition which must be satisfied by the energy density fluctuations of the 3D DQV in order to generate the Higgs mass. On the basis of equation (58), the Higgs mass can be seen as an emergent fact from the activity of the quantum vacuum energy density fluctuations at the generalized Compton wavelength. We have thus demonstrated how, in our model of 3D DQV with a variable energy density, Higgs field is not a primary physical reality but can be interpreted as the upper emergent manifestation resulting from the interplay of opportune underlying quantum vacuum energy density fluctuations involved at the Planck scale.

As regards the interaction of the Higgs (58) with the gauge bosons, one can express it via the following equation

$$\left|\left(i\frac{g}{2}\sigma_i W_\mu^i + i\frac{g'}{2}B_\mu\right)\Psi\right|^2 = \frac{\left[\frac{1}{k\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right)^{3/2}}+h\right]^2}{8} \times \left[g^2\left(W_\mu^1\right)^2 + g^2\left(W_\mu^2\right)^2 + \left(-gW_\mu^3 + g'B_\mu\right)^2\right] \quad (59)$$

where g, g' are the gauge couplings. In the light of relation (59), one finds that the masses of the vector bosons are the following:

$$M_W = \frac{g}{2k_W\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right)^{3/2}} \quad (60)$$

and

$$M_Z = \frac{\sqrt{g^2+g'^2}}{2k_Z\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right)^{3/2}} \quad (61),$$

where k_W is the constant associated to the condensate of virtual sub-particles of the vacuum corresponding to the appearance of a W boson and k_Z is the constant associated to the condensate of virtual sub-particles of the vacuum corresponding to the appearance of a Z boson. In this way, the weak mixing angle expressing the relationship between the masses of W and Z bosons in the Standard Model, in the approach of the 3D DQV becomes

$$\cos\theta_W = \frac{gk_Z}{k_W\sqrt{g^2+g'^2}} \quad (62).$$

Finally, one can also find a new formulation for the Fermi constant

$$G_F = \frac{\sqrt{2}}{4}k_W{}^2\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right)^3 \quad (63)$$

and here, by taking account of the numerical experimental value of the Fermi constant, one directly obtains the following constraint regarding the electroweak scale:

$$\frac{1}{k\left(\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_p^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right)^{3/2}} \sim 246\ GeV \quad (64).$$

Moreover, the model of the 3D DQV developed in this paper suggests a natural explanation for the anomalous results known as "negative mass square problem", in tuning with the results of [56] as regards a fundamental intrinsic relation between mass, gravity, space-time symmetry and the Higgs mechanism in a de Sitter (false) vacuum. In the light of the data on the solar and atmospheric neutrino [57], the neutrino oscillation is characterized by the following mass-squared difference for the neutrino oscillation, in two-flavour mixing approximation, which implies the existence of a strict link with the gravity-electroweak unification scale:

$\Delta m_{atm}^2 = 2{,}5 \cdot 10^{-3}\, eV^2; \quad \Delta m_{sol}^2 = 6{,}9 \cdot 10^{-5}\, eV^2$ (65).

In our approach, in the interaction vertex a particle can be described by an eigenstate of the de Sitter Casimir invariants, given by relation

$$I_1' = k^2\left[\mu^2 c^2 \pm \frac{\hbar^2}{2r_0^2}\right] \quad (66)$$

where r_0 is the de Sitter radius, which is ultimately associated and derived from the more fundamental generalized Compton wavelength (37), namely:

$$r_0^2 = \left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2 \quad (67).$$

By taking account [58, 59], the state (66), assumes the form of a linear superposition of two different mass eigenstates related to the condensate of the virtual particles of the 3D DQV

$$m_1^2 = k^2\left\{\mu^2 + \frac{\hbar^2}{2c^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right]}\right\}, \qquad m_2^2 = k^2\left\{\mu^2 - \frac{\hbar^2}{2c^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right]}\right\} \quad (68)$$

with equal weights. Moreover, by following [60], the mass-squared difference (65) can be associated directly with the unification scale M_{unif} of gravity and electroweak scale on the basis of relation

$$\Delta m^2 = \frac{8\pi}{3}k^2\left(\frac{M_{unif}}{m_{Pl}}\right)^4 m_{Pl}^2 \quad (69).$$

Now, in our approach, the variable energy density of the 3D DQV, at the scale represented by the generalized Compton wavelength, in the gravito-electroweak vertex, has the fundamental effect of determining the emergence of an exact bi-maximal mixing for neutrinos, and therefore at this scale the condensate of the virtual particles of the medium is responsible of the generation of the mass-squared difference between atmospheric and solar neutrinos:

$$\Delta m^2 = \frac{\hbar^2 k^2}{2c^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2 + \left(\beta l_p^2 \frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right]} \quad (70)$$

for both the right and left handed fields. Equation (70) physically means that the mass-squared difference between atmospheric and solar neutrinos is an emergent effect from the condensate of the virtual sub-particles of the 3D DQV close to the Planck scale.

Now, by equating (69) and (70), one can obtain an expression for the gravito-electroweak scale M_{unif} in the 3D DQV ruled by generalized uncertainty relations as follows

$$\frac{8\pi}{3}k^2\left(\frac{M_{unif}}{m_{Pl}}\right)^4 m_{Pl}^2=\frac{\hbar^2 k^2}{2c^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_P^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right]}\quad (71).$$

Equation (71) yields the following expression of the unification scale

$$\left(M_{unif}\right)^4=\frac{3\hbar^2 m_{Pl}^2}{16\pi c^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_P^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right]}\quad (72)$$

namely

$$M_{unif}=\frac{1}{2}\left(\frac{3\hbar^2 m_{Pl}^2}{\pi c^2\left[\left(\frac{\beta\hbar c}{\Delta\rho_{qvE}V}\right)^2+\left(\beta l_P^2\frac{\Delta\rho_{qvE}V}{\hbar\ c}\right)^2\right]}\right)^{1/4}\quad (73).$$

On the basis of relation (73), in our model of 3D DQV, the gravito-electroweak scale M_{unif} turns out to be directly determined by the generalized Compton wavelength, but turns out to be independent of the parameter k indicating the size of the condensate of the virtual particles of the background. In this way, the mass-squared difference (70) of neutrinos determined by the activity of the vacuum at the Planck scale and associated with the virtual particles of the 3D DQV, lead to corresponding values of the unification scale for solar and atmospheric neutrinos respectively

$M_{unif(atm)}\approx 14{,}5\,TeV;\qquad M_{unif(sol)}\approx 5{,}9\,TeV$ (74)

which turn out to be in good agreement with the results obtained in [55] as well as in other previous theories of electroweak unification [61-63]. The originality of this approach lies in the fact that the unification scale for solar and atmospheric neutrinos appears as an emergent phenomenon by starting from the activity of the virtual particles of the 3D DQV close to the unifying scale represented by the generalized Compton wavelength.

The approach developed in this paper introduces the insight to consider the generalized Compton wavelength as the fundamental scale at which the elementary processes taking place among the virtual particles of the 3D DQV lead to a unifying treatment of several issues related to the Standard Model. In this picture, maybe also the hierarchy problem (as well as maybe the gauge symmetries) could be resolved as a consequence of the specific behaviour of the quantum vacuum energy density fluctuations and, in particular, near to the scale M_{unif} associated with the virtual particles of the background generating the gravity-electroweak unification scale and which is given by equation (73).

On the other hand, a key theoretical issue in models of emergent Standard Model, is the scale of emergence. In this regard, by virtue of the link of the Higgs field as well as of the gravity-electroweak scale with the elementary properties of the vacuum, as formulated by equations (53) and (73), also the scale emergence can be seen as a collective result which derives from opportune condensates of elementary

energy density fluctuations of the 3D DQV associated with the activity of the virtual particles of the background.

Strictly related to the issue of the scales in the Standard model is the issue of the cosmological constant, that turns out to receive contributions from the physical vacuum. In our model of 3D DQV, these contributions can be formulated as follows:

$$\rho_{vac} = \rho_{qvE} + \rho_{potential} + \rho_{\Lambda} \quad (75)$$

where $\rho_{potential}$ is the potential energy density given by equation (51) and ρ_{Λ} is a renormalized version of the bare gravitational term [64, 65]. The vacuum energy density (75) turns out to be renormalization scale invariant, is directly responsible of the accelerating expansion of the Universe and is independent of the way it is calculated, namely

$$\frac{d}{d\mu^2}\rho_{vac} = 0 \quad (76).$$

In the light of its explicit μ^2 dependence and of the network of the virtual particles of the 3D DQV, the contributions to the quantum vacuum energy density ρ_{qvE} in equation (75) are scale dependent. In line with the results obtained in [2], in our model of 3D DQV whose geometry is ruled by the generalized Compton wavelength (37), one finds the following results: deep in the ultraviolet regime one has asymptotic freedom, while in the infrared confinement and dynamical chiral symmetry occur. The Higgs potential turns out to be renormalization scale dependent as a consequence of the scale dependence of the Higgs mass and Higgs self-coupling, which can be ultimately seen as the consequence of the processes of the virtual particles of the 3D DQV on the basis of equation (53) and determines the stability of the electroweak vacuum ultimately emerging from the unification scale (73).

Finally, we must remark that recently some issues seem to put at risk the theoretical implant of the Standard Model. In particular, scenarios towards a new physics could be opened by the so-called g-2 anomaly, regarding the discrepancy between theory and data of the magnetic dipole moment of the muon. Up to date the most part of physical explanations of the muon g-2 discrepance invoke new scalar fields, for example axions. In [66] an alluring potential solution to the muon g-2 anomaly has been suggested in terms of heavy axion-like particle with couplings to leptons and photons, which provides a tantalizing potential solution to the muon g-2 anomaly. However, this recent approach which invokes axions does not manage to specify the origins of the axion couplings and other relevant degrees of freedom and this could be the clue of the existence of new fundamental particles existing in nature, that could be probed in future searches. In the light of the considerations made in this paper, the perspective is opened that these new fundamental particles, which take account the origin of axions, could be the virtual sub-particles of the 3D DQV, associated with the quantum vacuum energy density fluctuations at the generalized Compton wavelength. In this regard, further research will give you more information.

5. Conclusions

The model of a 3D DQV defined by a variable energy density intended as primary physical reality, by starting from a generalized uncertainty relation measuring the deformation of the geometry of the background near the Planck scale, leads to a suggestive unification of the microscopic regime of elementary particles and the macroscopic domain of black holes as emergent forms of collective organization which derive from more elementary objects of the DQV, in other words to the existence of a fundamental scale where Compton wavelength and Schwarzschild radius are unified. A generalized Compton wavelength describing the ultimate microscopic geometry of the 3D DQV emerges as the fundamental entity that introduces compelling scenarios of unification for the beyond Standard Model physics. Opportune condensates of quantum vacuum energy density fluctuations which take place at the fundamental scale represented by the generalized Compton wavelength can be seen as the fundamental structures which give rise to the appearance of particles of the Standard Model at the Planck scale and, conversely, can be seen as the Planck signature of Standard Model particles. Moreover, the elementary processes characterizing the activity of the 3D DQV at the generalized Compton wavelength imply that Higgs field manifests itself as a pattern of collective organization, lead to an emergent unification of the gravity-electroweak scale that is responsible of the mass-squared differences between solar and atmospheric neutrinos and introduce the possibility of a treatment of the hierarchy problem and of the gauge symmetries of the Standard Model in an emergent key, in terms of the collective features regarding the underlying activity of the virtual sub-particles of the vacuum characterizing this unification scale ultimately deriving from the generalized Compton wavelength. In the light of the considerations made in this paper, the model of the 3D DQV with a variable energy density, whose ultimate geometry is associated with the generalized Compton wavelength, can be considered a relevant attempt to provide a description of the so-called "quantum foam" in epistemological affinity with J.A. Wheeler's program It from Bit (or Qbit) directed to describe the emergent features of space, time and matter as vehicled expressions of an informational matrix "at the bottom of the world" [67] and, at the same time, turns out to be compatible with an emergent view of physics. Although some improvements are obviously needed in order to clarify various aspects, the perspectives opened by the 3D DQV model can be considered a significant path directed to reach the unifying dreams of theoretical physics and in particular for the beyond Standard Model physics.

References:

1. SD Bass, "Emergence in particle physics", *Acta Physica Polonica B* **48**, 10, 1903-1908 (2017).
2. SD Bass and J Krzysiak, "Vacuum energy with mass generation and Higgs bosons", *Physics Letters B* **803**, 135351 (2020).
3. SD Bass, "Emergent gauge symmetries and particle physics", arXiv:2001.01705v1 [hep-ph] (2020).
4. S Biondini, D Boer and R Peeters, "The hierarchy problem and fine-tuning in a decoupling approach to multi-scale effective potentials", *Physical Review D* **104**, 036013 (2021).
5. PJE Peebles and B Ratra, "The cosmological constant and dark energy", *Reviews in Modern Physics* **75**, 3, 559-606 (2003).
6. EJ Copeland, M Sami and S Tsujikawa, "Dynamics of dark energy", *International Journal of Modern Physics D* **15**, 11, 1753-1935 (2006).
7. V Sahni and A Starobinsky, "The Case for a Positive Cosmological-Term", *International Journal of Modern Physics D* **9**, 373-444 (2000).
8. T Padmanabhan, "Cosmological constant—the weight of the vacuum", *Physics Reports* **380**, 5-6, 235-320 (2003).
9. J Martin, "Everything you always wanted to know about the cosmological constant problem", *Comptes Rendus Physique* **13**, 566-665 (2012).
10. J Solà, "Cosmological constant and vacuum energy: old and new ideas", *Journal of Physics: Conference Series* **453**, 012015 (2013).
11. E Oks, "Brief review of recent advances in understanding dark matter and dark energy", *New Astronomy Reviews* **93**, 101632 (2021).
12. JE Horvath, "Which is the ontology of dark matter and dark energy?", *Cosmos and history: The Journal of Natural and Social Philosophy* **17**, 1, 326-344 (2021).
13. A Deur, "An explanation for dark matter and dark energy consistent with the Standard Model of particle physics and General relativity", *European Physical Journal C* **79**, 883 (2017).
14. D Fiscaletti and A Sorli, "Perspectives about quantum mechanics in a model of a three-dimensional quantum vacuum where time is a mathematical dimension", *SOP Transactions on Theoretical Physics* **1**, 3, 11-38 (2014).
15. D Fiscaletti and A Sorli, "Space-time curvature of general relativity and energy density of a three-dimensional quantum vacuum", *Annales UMCS Sectio AAA: Physica* **LXIX**, 55-81 (2014).
16. D Fiscaletti, *The timeless approach. Frontier perspectives in 21st century physics*, World Scientific, Singapore (2015).
17. D Fiscaletti, "About dark energy and dark matter in a three-dimensional quantum vacuum model", *Foundations of Physics* **46**, 10, 1307-1340 (2016).

18. D Fiscaletti and A Sorli, "About a three-dimensional quantum vacuum as the ultimate origin of gravity, electromagnetic field, dark energy … and quantum behaviour", *Ukrainian Journal of Physics* **61**, 5, 413-431 (2016).
19. D Fiscaletti and A Sorli, "Dynamic quantum vacuum and relativity", *Annales UMCS Sectio AAA: Physica* LXXI, pp. 11-52 (2016).
20. D Fiscaletti, "What is the actual behaviour of the electron? From Bohm's approach to the transactional interpretation… to a three-dimensional timeless non-local quantum vacuum", *Electronic Journal of Theoretical Physics* **13**, 35, 1-26 (2016).
21. D Fiscaletti and A Sorli, "About electroweak symmetry breaking, electroweak vacuum and dark matter in a new suggested proposal of completion of the Standard Model in terms of energy fluctuations of a timeless three-dimensional quantum vacuum", *Quantum Physics Letters* **5**, 3, 55-69 (2016).
22. D Fiscaletti and A Sorli, "Quantum vacuum energy density and unifying perspectives between gravity and quantum behaviour of matter", *Annales de la Fondation Louis de Broglie* **42**, 2, 251-297 (2017).
23. D Fiscaletti and A Sorli, "Quantum relativity: variable energy density of quantum vacuum as the origin of mass, gravity and the quantum behaviour", *Ukrainian Journal of Physics* **63**, 7, 623-644 (2018).
24. D Fiscaletti, "About dark matter as an emerging entity from elementary energy density fluctuations of a three-dimensional quantum vacuum", *Journal of Theoretical and Applied Physics* **14**, 203-222 (2020).
25. D Fiscaletti and A Sorli, "Generalized uncertainty relations, particles, black holes, and Casimir effect in the three-dimensional quantum vacuum", *Theoretical and Mathematical Physics* **214**, 1, 132-151 (2023).

26. G Amelino-Camelia, "Quantum gravity phenomenology", arXiv:0806.0339 (2008).
27. C Rovelli, "A new look at loop quantum gravity", arXiv:1004.1780v1 [gr-qc] (2010).
28. D Fiscaletti, "About non-local granular space-time foam as ultimate arena at the Planck scale". In: *Space-time geometry and quantum events*, I. Licata ed., Nova Science Publishers, New York (2014).

29. G 't Hooft, "How does god play dice? (Pre-)determinism at the Planck scale". In: *Quantum (Un)speakables, from Bell to quantum information*, R.A. Bertlmann and A. Zeilinger eds., Springer-Verlag, pp. 307-316 (2001).
30. G 't Hooft, "Quantum mechanics and determinism", arXiv:hep-th/0105105 (2001).
31. G 't Hooft "The fate of the quantum", arXiv:1308.1007 [quant-ph] (2013).
32. G 't Hooft, *The cellular automaton interpretation of quantum mechanics*, Springer, Heidelberg (2016).

33. I Licata, "Quantum mechanics interpretation on Planck scale", *Ukrainian Journal of Physics* **65**, 1, 17-30 (2020).
34. M Maggiore, "The algebraic structure of the generalized uncertainty principle", *Physics Letters B* **319**, 83-86 (1993).
35. F Scardigli, "Generalized uncertainty principle in quantum gravity from micro-black hole gedanken experiment", *Physics Letters B* **452**, 39-44 (1999).
36. L Petruzziello and F Illuminati, "Quantum gravitational decoherence from fluctuating minimal length and deformation parameter at the Planck scale", *Nature Communications* **12**, 4449 (2021).
37. P Bushev et al., "Testing of Quantum Gravity With Sub-Kilogram Acoustic Resonators", arXiv:1903.03346 (2019).
38. C Villalpando and S Modak, "Probing Quantum Gravity with Large Molecular Wave-packets", arXiv:1901.09696 (2019).
39. I Pikovski et al., "Probing Planck-scale physics with quantum optics", *Nature Physics* **8**, 393-397 (2012).
40. F Scardigli, G Lambiase and E Vagenas, "GUP parameter from quantum corrections to the Newtonian potential", *Physics Letters B* **767**, 242-246 (2017).
41. F Scardigli "The deformation parameter of the generalized uncertainty principle", *J. Phys. Conf. Ser.*, 1275, 012004 (2019).
42. S Das and EC Vagenas, "Phenomenological implications of the generalized uncertainty principle", arXiv:0901.1768v1 [hep-th] (2009).
43. BJ Carr, "The Black Hole Uncertainty Principle Correspondence", *Springer Proc. Phys.* **170**, 159-167 (2016).
44. X Calmet, BJ Carr and E Winstanley, *Quantum black holes*, Springer, Heidelberg-Berlin (2014).
45. MJ Lake, M Miller, RF Ganardi, Z Liu, S-D Liang and T Paterek, "Generalised uncertainty relations from superposition of geometries", arXiv:1812.10045v3 [quant-ph] (2019).
46. MJ Lake and B Carr, "The Compton-Schwarzschild relations in higher dimensions", arXiv:1611.01913 [gr-qc] (2016).
47. MJ Lake and B Carr, "Does Compton/Schwarzschild duality in higher dimensions exclude TeV quantum gravity?", *International Journal of Modern Physics D*, 1930001 (2018).
48. MJ Lake and B Carr, "The Compton-Schwarzschild correspondence from extended de Broglie relations", *Journal of High Energy Physics* **1511**, 105 (2015).
49. BJ Carr, JR Mureika and P Nicolini, "Sub-Planckian black holes and the generalized uncertainty principle", *Journal of High Energy Physics* **2015**, 07052 (2015).

50. J Carr, L Modesto and I Prémont-Schwarz, "Generalized uncertainty principle and self-dual black holes", arXiv:1107.0708 [gr-qc] (2011).
51. S Robles-Pérez and PF Gonzáles-Díaz, "Quantum state of the multiverse", *Physical Review D* **81**, 8, 083529 (2010).
52. I Licata and L Chiatti, "Timeless approach to quantum jumps", *Quanta* **4**, 1, 10-26 (2015).
53. L Chiatti and I Licata, "Particle model from quantum foundations", *Quantum Studies: Mathematics and Foundations* **4**, 181-204 (2017).
54. L Chiatti, "The transaction as a quantum concept," arXiv.org/pdf/1204.6636 (2012).
55. JL Diaz-Cruz, "The Higgs profile in the Standard Model and beyond", *Revista Mexicana de Fisica* **65**, 5, 419-439 (2019).
56. I Dymnikova, "Mass, spacetime symmetry, de Sitter vacuum, and the Higgs mechanism", *Symmetry* **12**, 634 (2020).
57. S Pakvasa and JW Valle, "Neutrino Properties Before and After KamLAND", *Proc. Indian Natl. Sci. Acad. 70A*, 189–222 (2004).
58. AV Bednyakov, BA Kniehl, AF Pikelner and OL Veretin, "Stability of the elec-troweak vacuum: gauge independence and advanced precision", *Physical Review Letters* **115**, 201802 (2015).
59. KG Zloshchastiev, "Spontaneous symmetry breaking and mass generation as built-in phenomena in logarithmic nonlinear quantum theory", *Acta Physica Polonica B* **42**, 261-292 (2011).
60. D Ahluwalia and I Dymnikova, "Spacetime as origin of neutrino oscillations", *International Journal of Modern Physics D* **12**, 1787–1794 (2003).
61. I Antoniadis, "A Possible new dimension at a few TeV", *Physics Letters B* **246**, 377–384 (1990).
62. G Dvali and AY Smirnov, "Probing Large Extra Dimensions with Neutrinos", *Nuclear Physics B* **563**, 63–81 (1999).
63. N Arkani-Hamed, S. Dimopoulos, G. Dvali and N. Kaloper, "Infinitely Large New Dimensions", *Physical Review Letters* **84**, 586–589 (2000).
64. S Weinberg, "The cosmological constant problem", *Reviews of Modern Physics* **61**, 1 (1989).
65. J Sola, "Cosmological constant and vacuum energy: old and new ideas", *J. Phys. Conf. Ser.* **453**, 012015 (2013).
66. MA Buen-Abad, J. Fan, M. Reece and C. Sun, "Challenges for an axion explanation of the muon g-2 measurement", *Journal of High Energy Physics* **09**, 101 (2021).
67. JA Wheeler, "Information, physics, quantum: The search for links". In: *Complexity, Entropy, and the Physics of Information*, W. Zurek ed., Addison-Wesley, Redwood City, California (1990).